Advanced Atomic Clock Standards

Robert L. Tjoelker

December 8, 2000

End to End capability in state of the art Frequency and Timing Research, Development, Implementation, and Testing

Deep Space Network Frequency and Timing Subsystem & Developments
- Atomic Frequency Standards (H-masers, Trapped Ion Standards)
- Cryogenic Sapphire Oscillator (CSO)
- Ultra Stable Fiber Optic Frequency Distribution (FODA)
- Master Clock, Time Insertion Distribution, TCT's
- Phase Calibration Generators (PCG) and tone generation
- GPS & TWS Frequency Transfer and Time Synchronization
- Frequency and Time Stability Analyzers

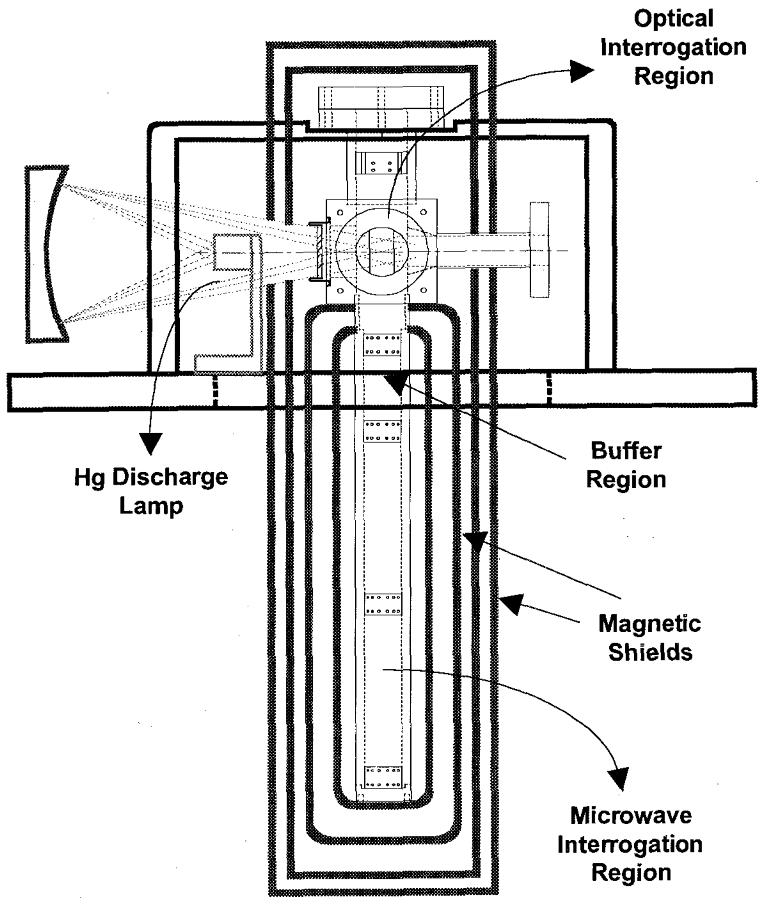
Flight Atomic Clock Development
- GPS Trapped Ion Atomic Clock
- Laser Cooled Atomic Clocks for Scientific applications on the Space Station
- Flight Oscillator testing and Component Evaluation

Frequency Standards Test Laboratory
- Oscillator Performance & Environmental Testing
- Low Noise Measurement Technology Development
- Advanced Frequency Stability Measurement Techniques

Mercury Ion Clock
Linear Ion Trap Standards (LITS)

- LITS and LITE Hg Ion Clock Applications
  - Deep Space Network
  - Timekeeping: US Naval Observatory
  - Space Based Applications
    - GPS Development
    - Autonomous navigation
  - Commercial development
    (10-100x improved stability in small package)

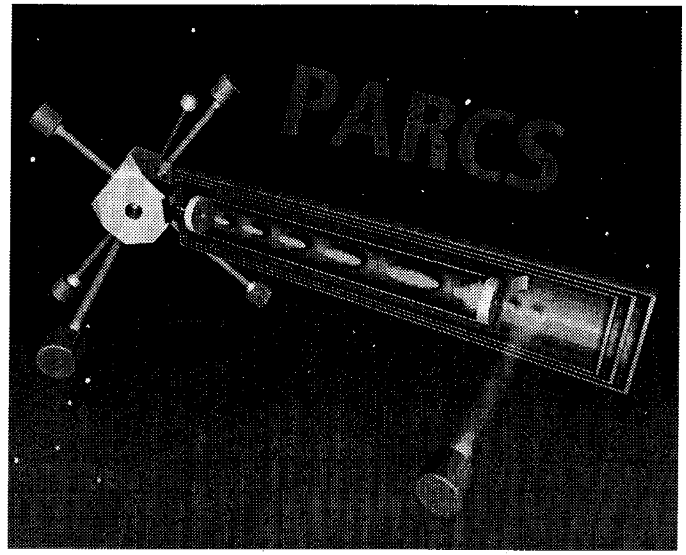
Continuous operation, Highest stability
- No Lasers
- No Cryogenics
- No Microwave Cavity



LITE Frequency Standard

PARCS PROJECT OVERVIEW

LCAP -- Primary Atomic Reference Clock in Space



Salient Features

- *Operates on Board the International Space Station*
- *First Utilization of Laser Cooling in Space*
- *Accuracy of 10^{-16}*
- *Launch date: 2005*
- *Operational life: 0.5 - 1 year*

Science

- *Measure the gravitational red-shift and second order doppler shift by comparing clock frequency to a ground unit*
- *Test local position invariance by comparing clock frequency to a second clock utilizing different atoms.*
- *Improve on the world wide realization of the second*
- *Precision Measurement of clocks at the 10^{-16} level*
- *Study GPS signals*
- *Perform precise frequency distribution to clocks around the globe*

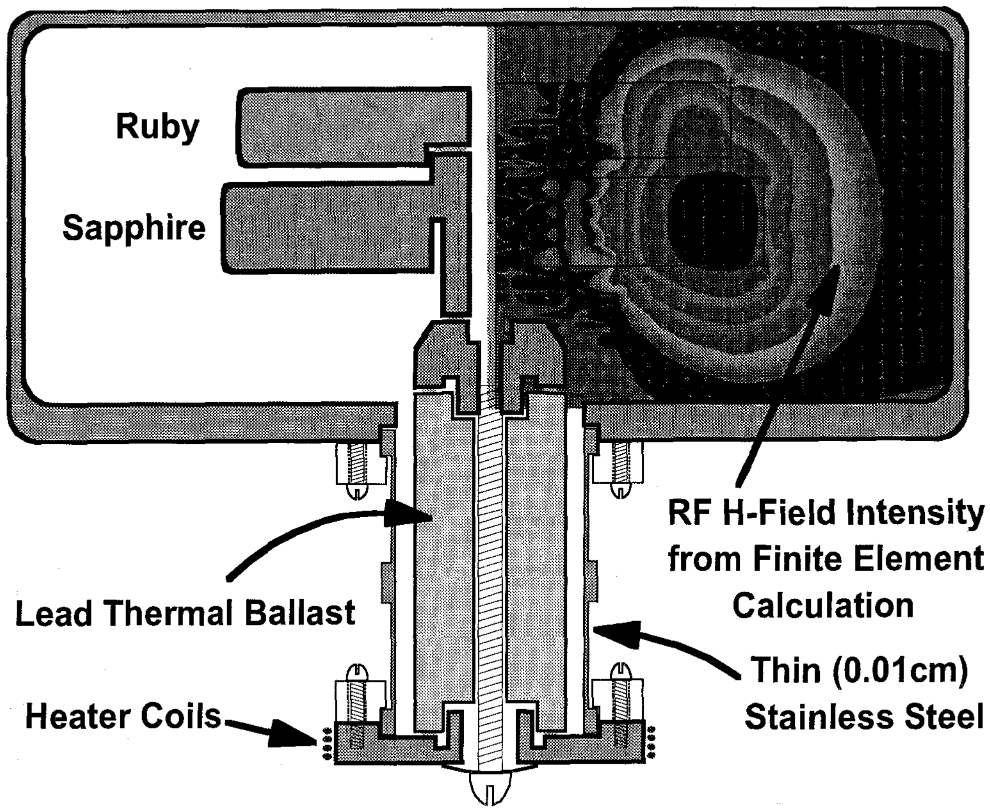
Compensated Sapphire Oscillator (CSO)

- Primary Resonator: Sapphire dielectric disk
- Compensation Element: Ruby disk.
- Temperature variations change the physical dimension of Sapphire (and frequency).

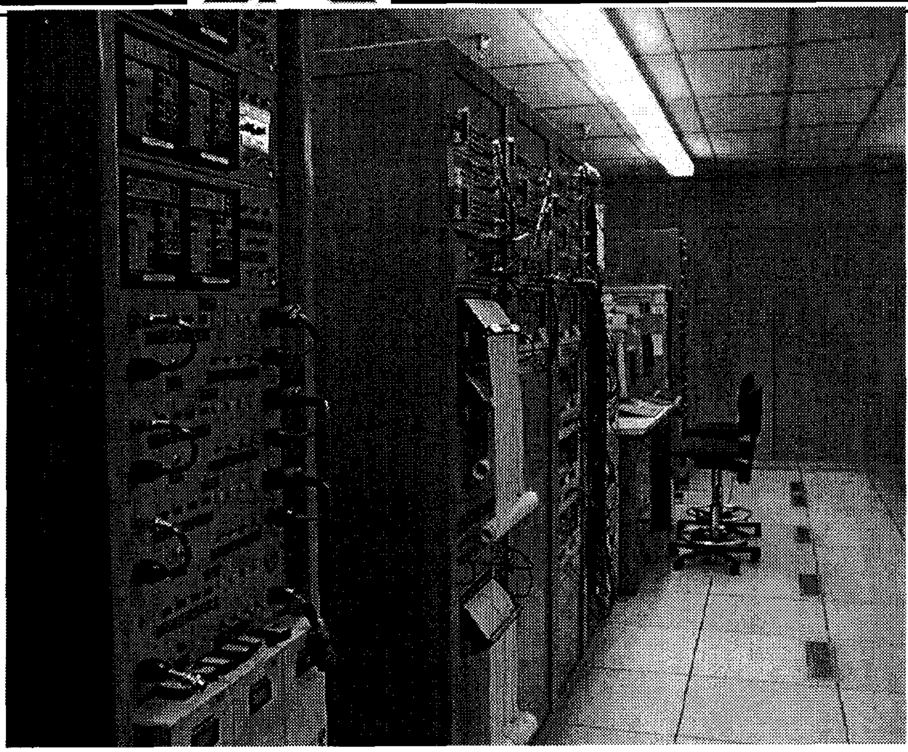
  Compensated by a change in the rf-electrical size of the <u>coupled</u> Sapphire/Ruby resonator.

  Temperature changes thus make no frequency changes at ~ 8 K.

- Closed-cycle Helium Refrigerator enables continuous operation for 1 year.
- Output frequency stability 3×10^{-15}, 1- 300 s.
- DSN Applications:
  - Cassini Radio Science Mission
  - Super Local Oscillator



Frequency and Timing Advanced Instrument Development Group
Frequency Standards Test Laboratory (FSTL)



Major Capabilities:

- State of Art Frequency Stability References
- 12 Simultaneous Allan Variance Channels
- Environmental Testing
  Temperature, Humidity, Pressure, Magnetic, Acceleration

Major Customers:

- DSN Frequency Standard Qualification
- DSN Development & Implementation Testing
- Evaluation of New Technology Developments
- Testing Flight Oscillators, Systems, & Components

JPL

Clock Issues for GPS

- Availability of spacecraft clocks
- Concerns over small manufacturing base
- Future performance needs

Benefits of Hg+ LITS for GPS

- Hg+ LITS provides significantly improved performance
- LITS technology has been proven on the ground
- LITS is amenable to reconfiguration for use in space
- JPL is recognized for clock development *and* in space instrument development
- LITS technology could be transferred for future industrial production

Development Overview: Approach

- The GPS/LITS Project miniaturizes existing DSN clock technology, to fly on GPS.
    - develop to existing cesium footprint

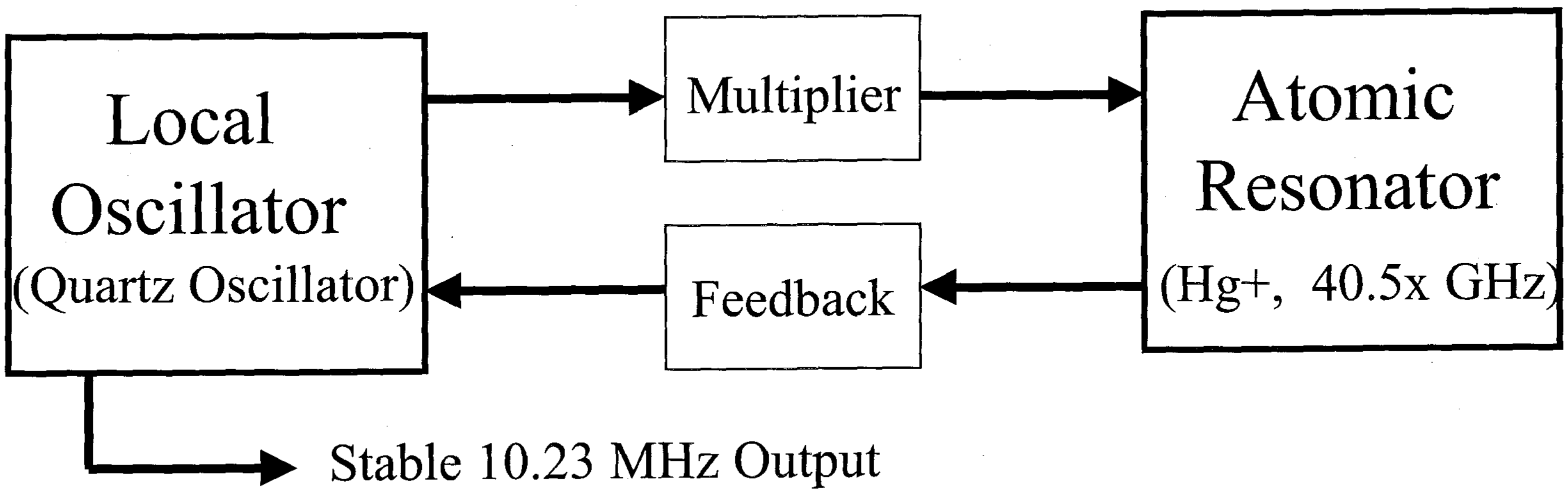
- GPS/LITS will provide a better performance than the current cesium and rubidium atomic clocks flown for GPS.
    - present goal is 10x improvement at all averaging times

- Over a 4-year period,

  - a ***breadboard*** will show proof-of-concept by reducing the current multi-100 lb, 1000-W instrument to a 50 lb, 80W breadboard and verify performance.
  - a ***laboratory prototype*** will be developed to continue miniaturization to be comparable to cesium atomic clocks and be flight qualifiable.
  - a ***flight demonstration unit*** will have a design goal of 10 years operational life and space-qualified as a 3-year lifetime instrument

- The design impacts for 10-year lifetime requirements will be extrapolated for the Flight Instrument.

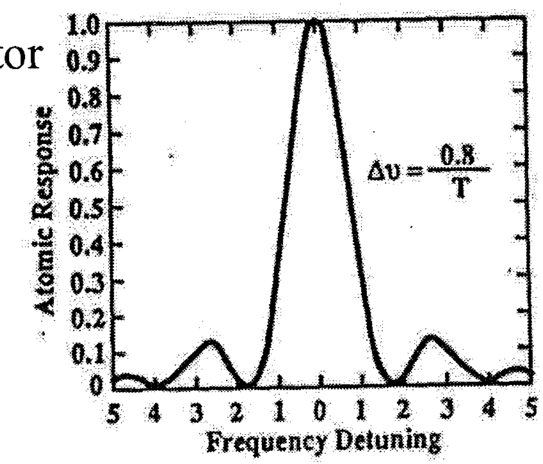
Atomic Frequency Standards



- Voltage controlled oscillator is locked to the atomic resonator

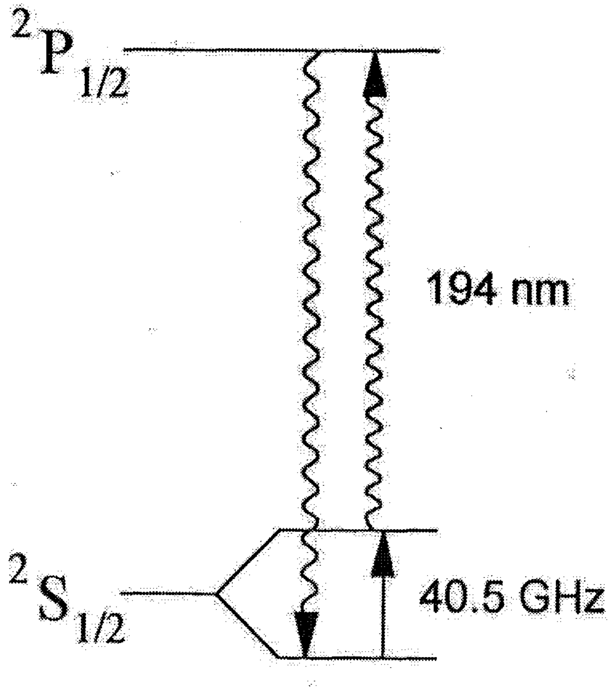
- Atomic transition is selected that is least sensitive to environmental effects and can be easily measured.

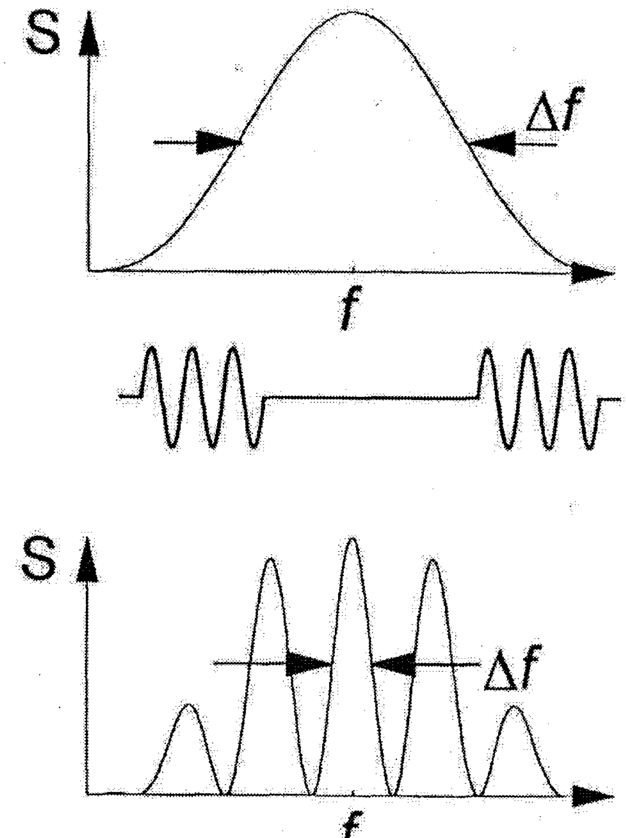
- Short term output stability depends on Local Oscillator, Long term stability determined by the atomic resonator.



Hg+ Trapped Ion Frequency Standard Principles

Ion loading, State selection (optical pumping), Microwave interrogation





$$Q = \frac{f}{\Delta f} > 2 \times 10^{12}$$

Ion Trapping and Interrogation Cycle

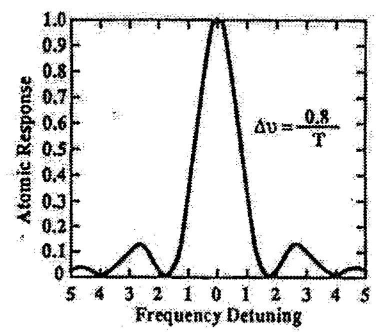
1. **Mercury atoms are ionized and trapped in a Linear Ion Trap (LITS).**

2. **Ion energy state is controlled by 194 nm light from a UV lamp (Optical Pumping)**

3. **Ions are irradiated by 40,507,347.9968 Hz microwave energy produced by Local Oscillator (LO)**

   a) If 40.507xx GHz is the "correct" frequency, ions scatter 194 nm UV light into a photon detector, otherwise ions remain transparent to UV light.

   b) Detected UV light is used to determine "frequency adjustment" of the LO.



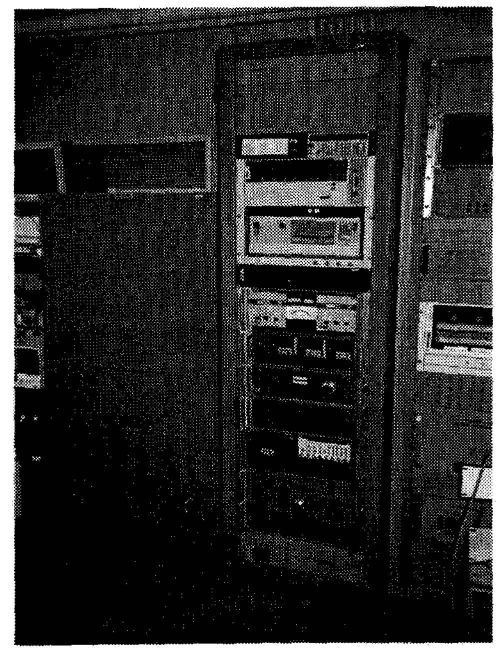
4. **Local Oscillator is steered to provide frequency reference with the stability of the atomic transition**

Major Features of Hg+ Ion Frequency Standards

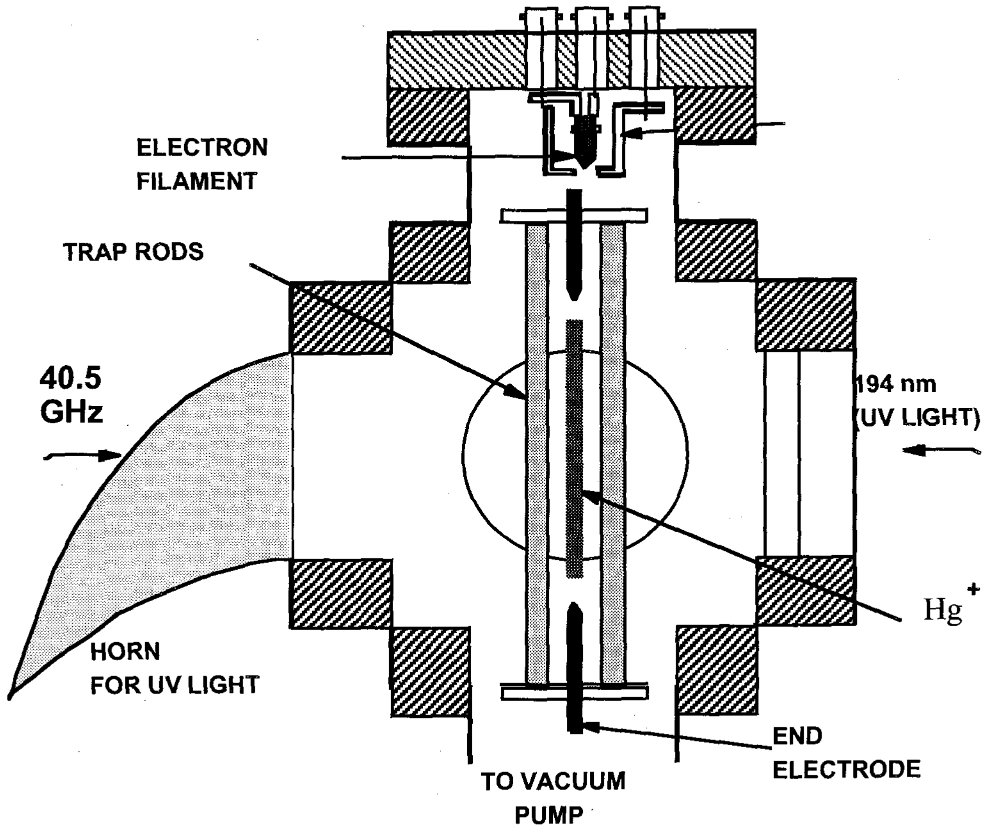
- Trapped ions: No wall collisions & can be electrically transported
- Atomic state control: Optical pumping with ^{202}Hg rf discharge lamp
- Ion loading/ cooling: Collisions with buffer gas (typically Helium)
- High Q atomic transition (40.5xx GHz)
  - **Small Magnetic Sensitivity**
  - **Small Temperature Sensitivity**
- Practical engineering and operational advantages
  - **No Lasers**
  - **No Cryogenics**
  - **No Microwave Cavity**
  - **No Atomic Beam**

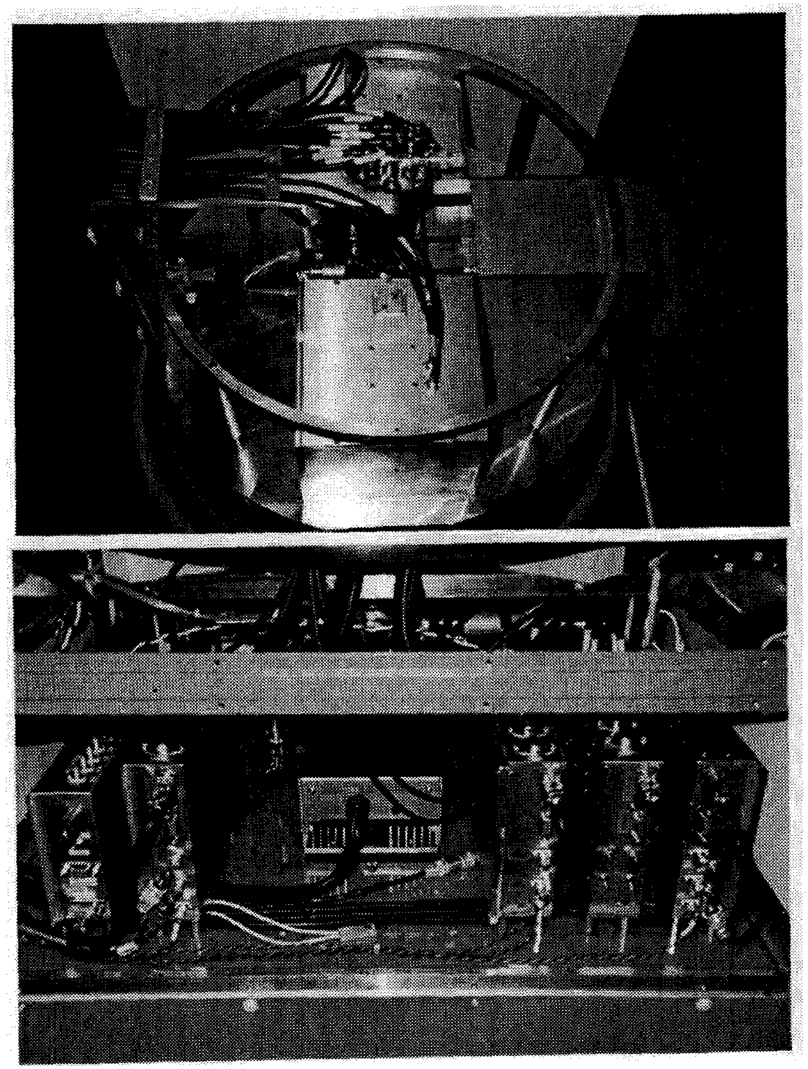
Ground Based DSN LITS Design Drivers

- Highest Frequency Stability Performance:
  - DSN: High stability at all averaging intervals, LO
  - USNO: Long Term Stability for Timekeeping
- Reliable: Continuous, autonomous operation at remote sites
- Maintainable: Modular, Accessible, Long MTBM
- Maximum technical return with fixed budget:
  - Design with off-the-shelf components where practical
- Little consideration was given to size, mass, power.

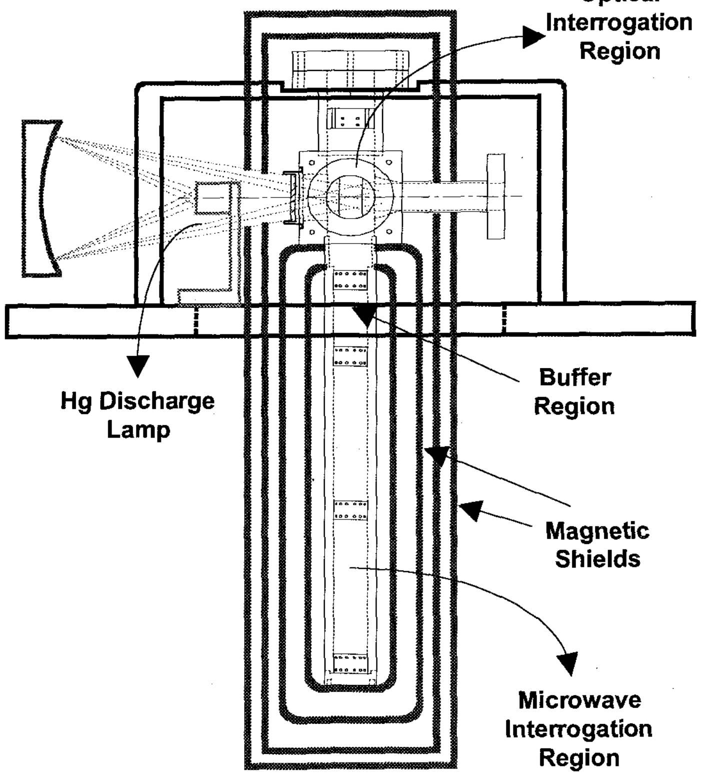


Linear Ion Trap Standard (LITS)

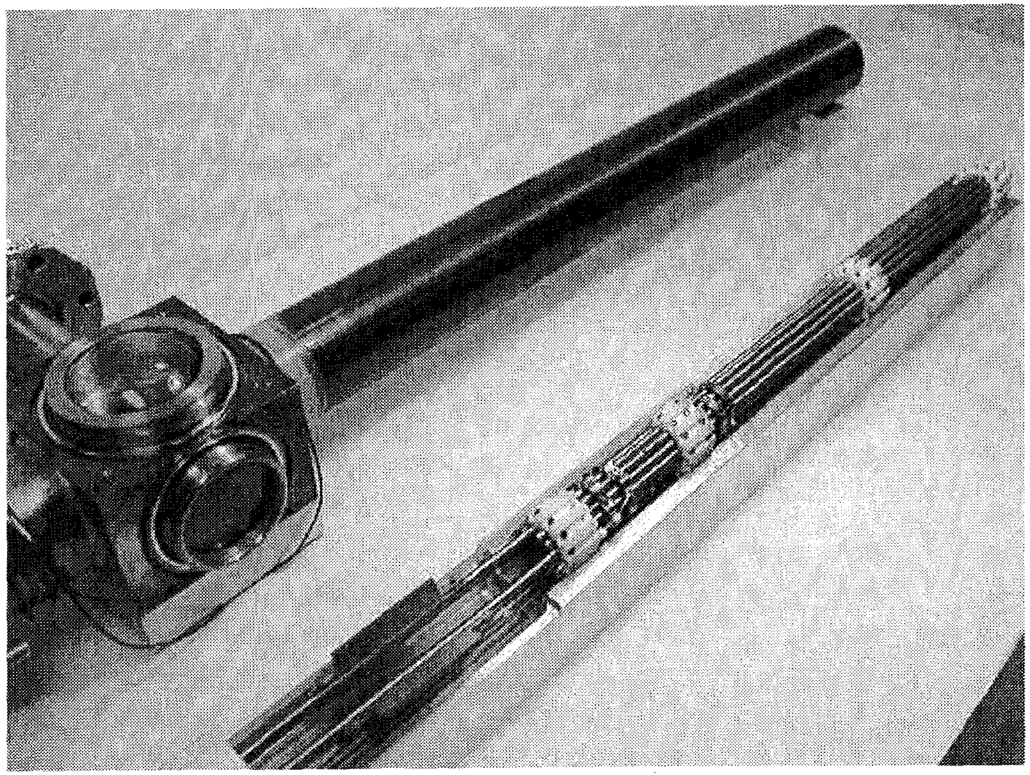




LITE "Supershuttle" Frequency Standard



LITE Physics Package



Vacuum Jacket, Windows, & 12 rod Multi-pole Trap

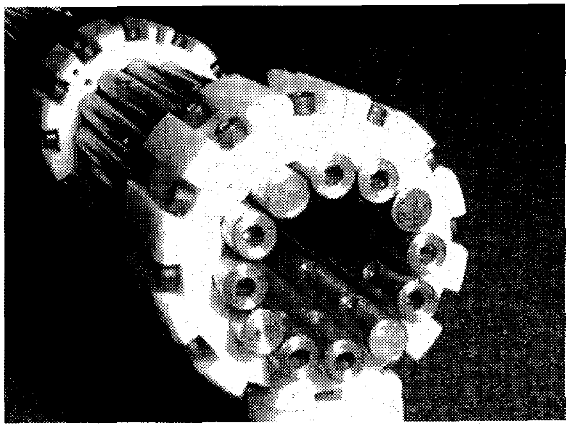
- Multipole trap provides major improvement in long term stability (>20x) over previous LITS
- Major advance in allowing small packaging & engineering simplifications
- Stability floor of $1\text{x}10^{-16}$ expected.

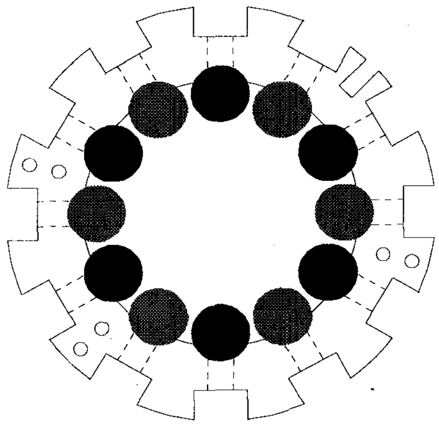
Technology Issue - LongTerm Stability

- Multi-pole Trap (2k rods) was investigated theoretically and found to be greater than 20x less sensitive to variations in quantity of trapped ions.

- Temperature Sensitivity stems (mostly) from variations of the number of trapped ions with ambient temperature changes and the consequent Doppler pulling of the clock frequency.

$$\frac{\Delta f}{f} = -\frac{3k_B T}{2mc^2}\left(1+\frac{2}{3}N_d{}^k\right) \qquad N_d{}^k = \frac{1}{k-1}.$$

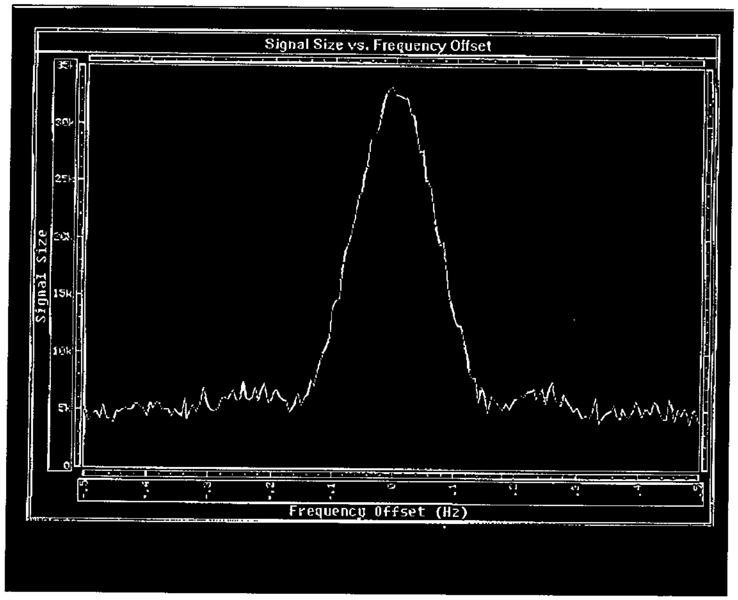


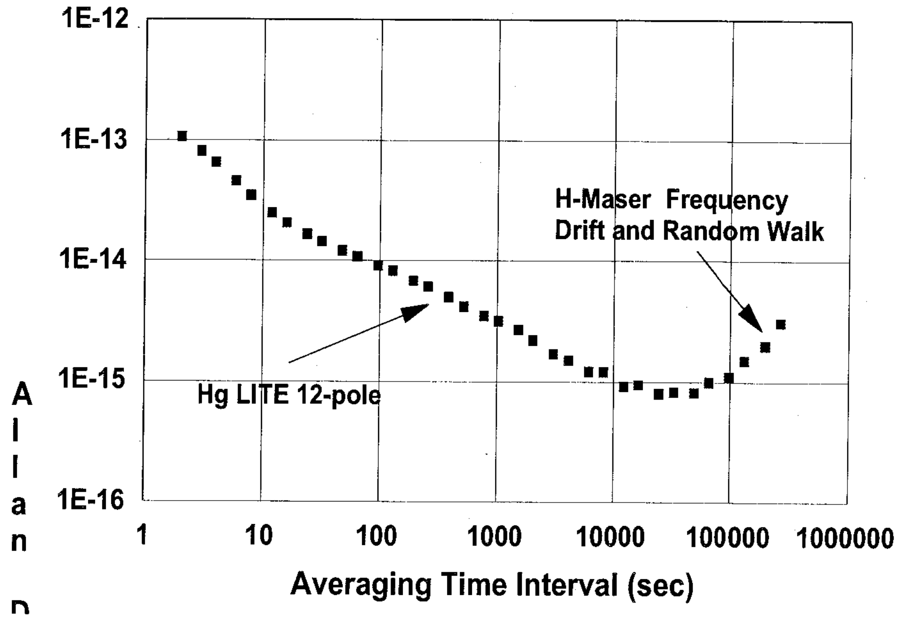


12- Pole Trap - Test Results

JPL

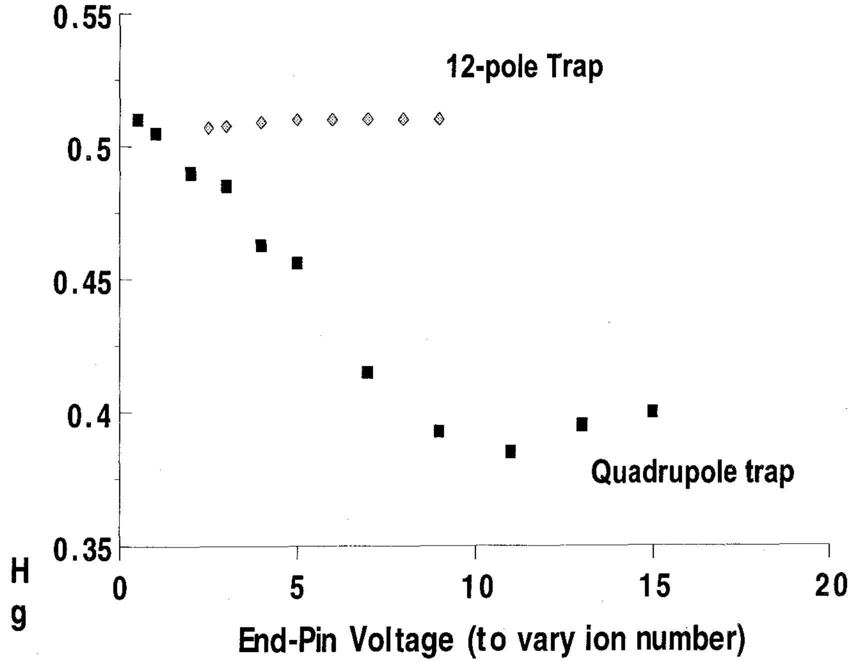
- Measured stability at $1\text{-}2\times10^{-15}$ in a non-regulated environment during ambient temperature variations of ~1 C. By comparison, H-maser requires thermal regulation to ~ 0.1 mK stability to reach 10^{-15} frequency stability.
- Stability data below taken in a temperature controlled chamber (~ 50 mK)
- Frequency Stability measurement of the LITE 12-Pole beyond 10^4 seconds is limited by H-maser reference stability



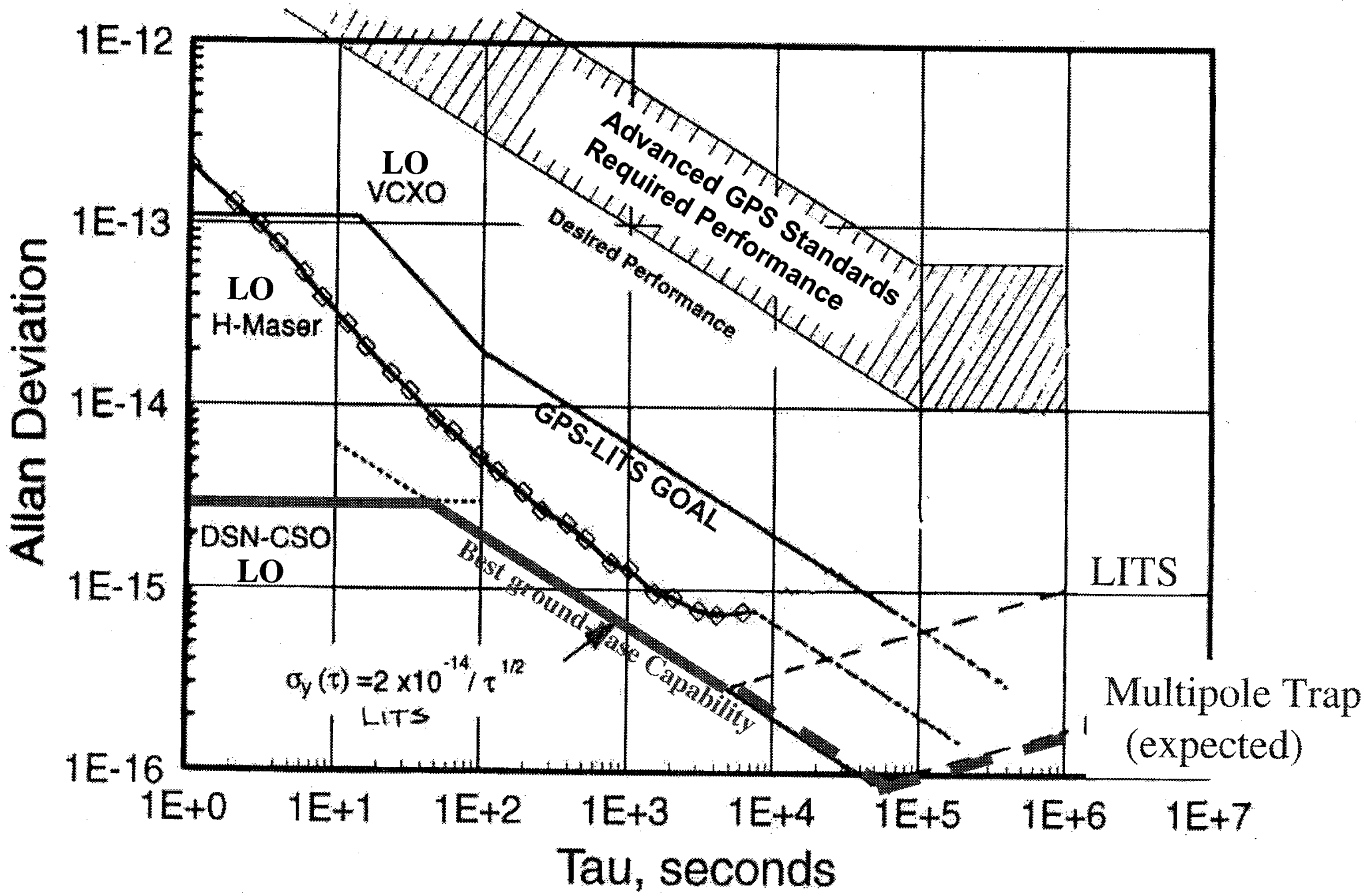


Hg Ion Clock - Test Results

- **12-Pole Ion Trap has reduced the clock frequency sensitivity to changes in the number of trapped Hg Ions.**
  - **80 mHz ($2x10^{-12}$) frequency changes with ion number are practically eliminated**
- **For some applications (Space GPS Clock, One-Way Nav Deep Space Clock), no active temperature regulation of the clock package may be necessary. Saves mass, power, and $$$.**



Performance Capability with Hg+ Standards



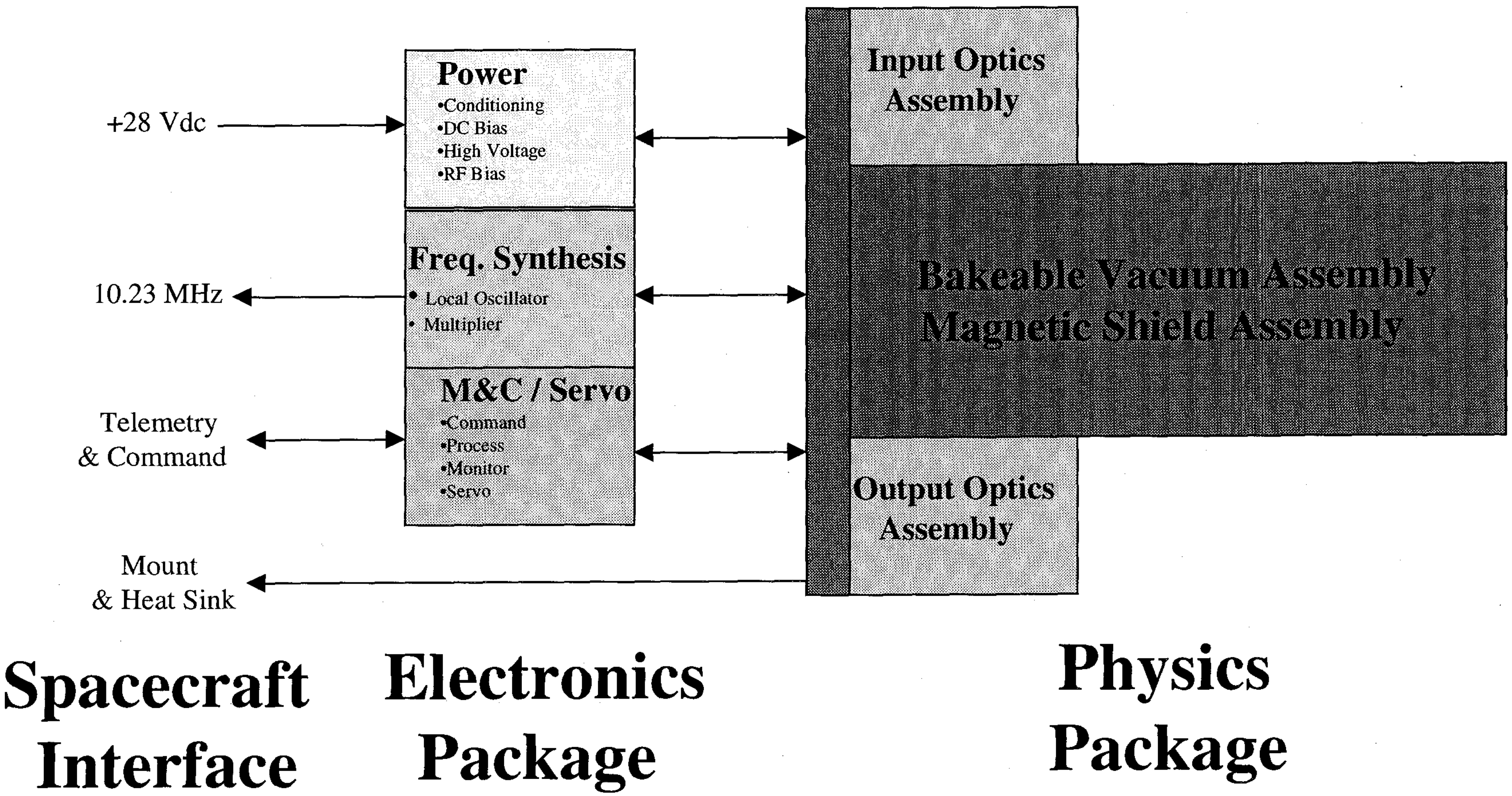
Drivers and Challenges of the Trapped Ion GPS Design

- Ten times performance improvement over existing GPS clocks.
- Mass & power reduction: 1000 lbs to 40 lbs, 1000 watts to 40 watts
- Launch, flight, and orbit environment survivability:
  - Launch, insertion vibration and shock
  - SV radiation environment
  - Large Thermal and magnetic variations
- Operational and reliability considerations:
  - Single Clock Operational Life: 10 years (consumable, radiation, parts)
  - Autonomous operation, optimization, and diagnostics
- Manufacturability

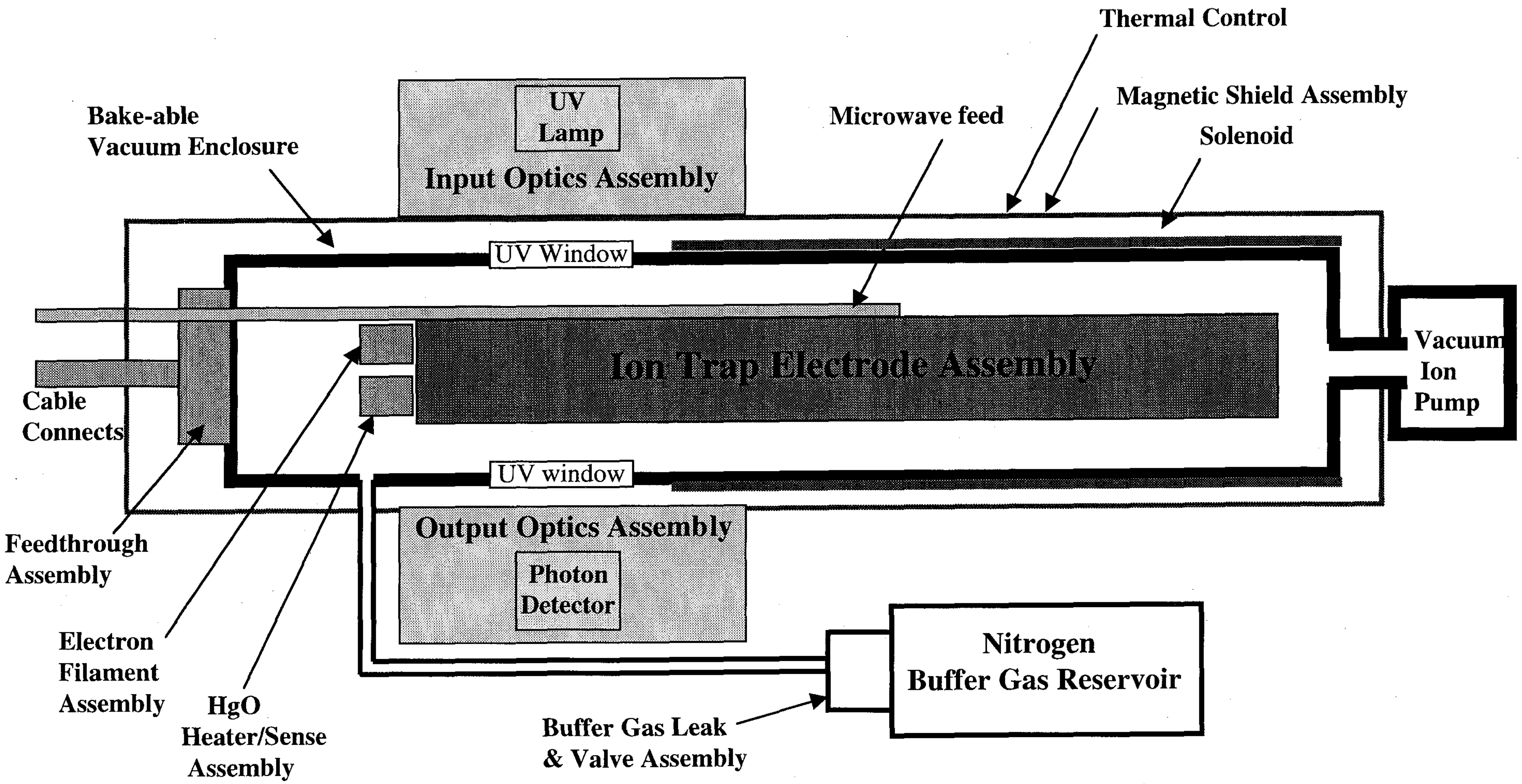
Recent Technology Developments & Progress

- Multi-Pole Ion Trap
  - 20x Second Order Doppler sensitivity reduction
  - increased long term stability
- Vacuum Pump & Buffer Gas
  - clock life, power, performance
  - ion pump, buffer gas & alternatives
- Hg+ Source
  - microgravity source, stability, power
- Physics Package Mechanical Design
  - electrode design and mount
  - buffer gas leak & valve
- Lamp/UV Source & Detector Development
  - in vacuum operation & thermal control
  - lifetime, power
- Electronic Development
  - first cut power budget for breadboard
  - lamp driver

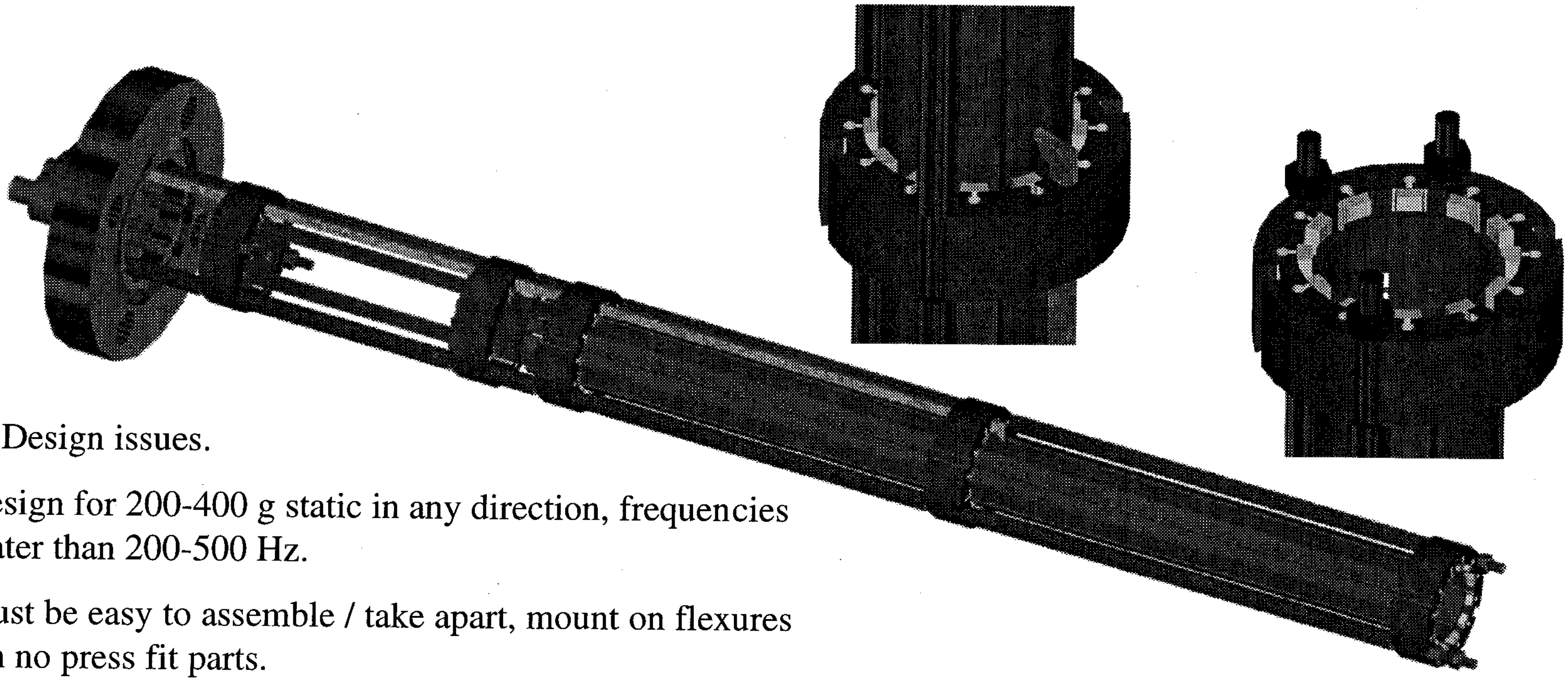
GPS LITS Instrument Block Diagram



GPS LITS Physics Package Block Diagram



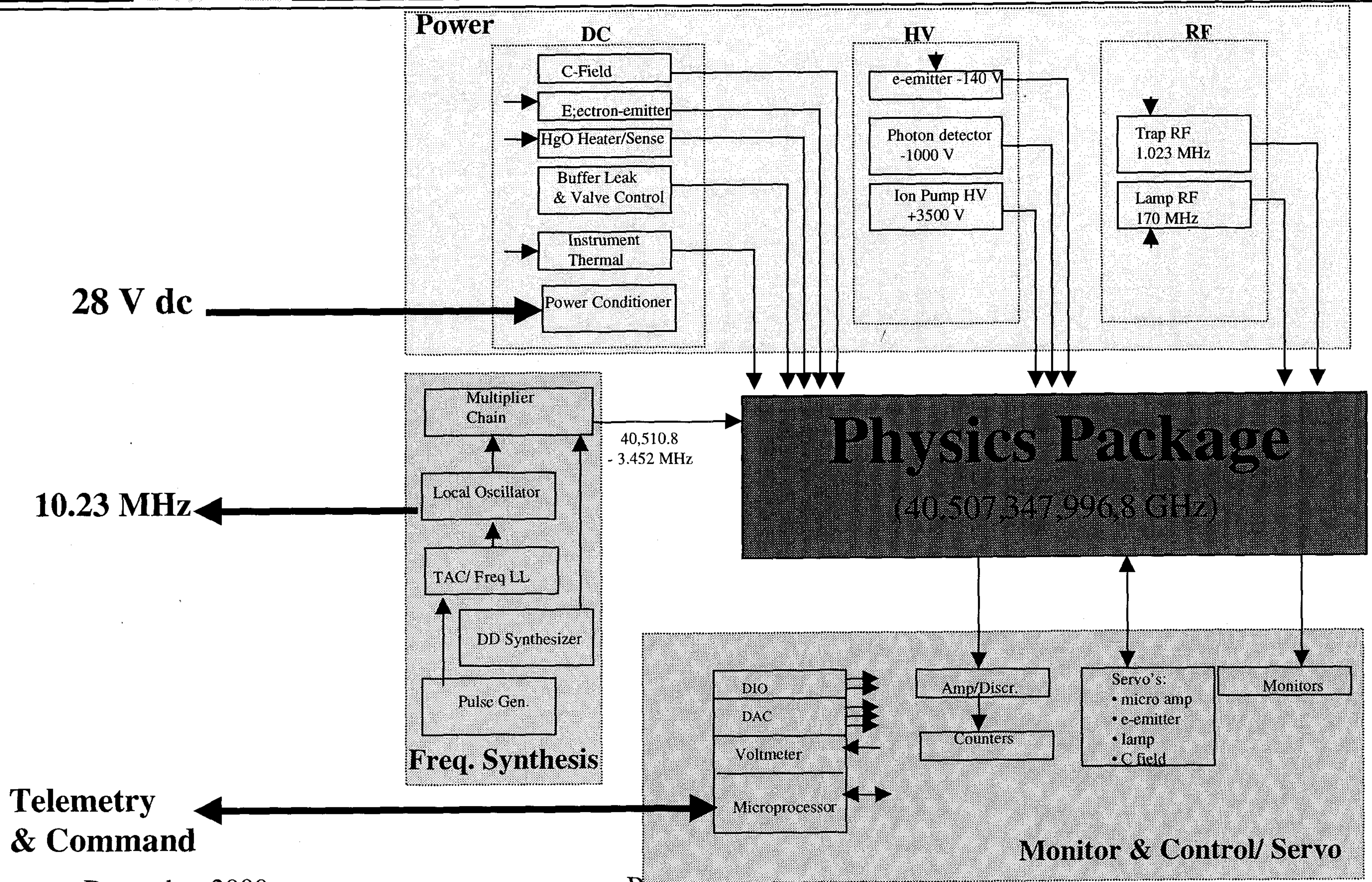
Trap Electrode Design For Flight



Prototype Design issues.

- –Design for 200-400 g static in any direction, frequencies greater than 200-500 Hz.
- –Must be easy to assemble / take apart, mount on flexures with no press fit parts.
- –Compatible with high vacuum - 400 °C bake out.
- –Non magnetic and vacuum compatible materials selection
- –Implement segmented design using EDM.

GPS LITS Electronic Block Diagram



GPS LITS Breadboard Electronic Assembly

Breadboard Phase: Power/Mass/Size Estimate

Electronic Assembly	Power (W)	Mass (oz.)	Size (inches)
Mercury Lamp RF Driver	6 ave/10 pk	12	5 x 4 x 0.7
Trap Electrode Driver	4	8	5 x 4 x 0.7
Electron Emitter	4	8	5 x 4 x 0.7
RF Mult/Freq LL	5	8	5 x 4 x 1
10.23 MHz VCXO	4	4	3.5 x 3.5 x 3.5
Main Freq Servo (TAC)	1.5	6	5 x 4 x 0.7
C-Field Current	1.5	6	4 x 4 x 0.7
Photo Detector HV	2	8	5 x 4 x 1.5
ION Pump HV	3	12	6 L x 2 D
Servo DDS	4	5	5 x 4 x 1
Microprocessor	5	16	10 x 6 x 1
Photocount Preamp Discrim	.01	4	2 x 2 x 1
Power Conditioning	13 Ave/15 pk	12	4 x 5 x 1
Total:	53 ave/59 pk	109 oz. (7 lbs)	approx. 6.6 inch cube